PAPER • OPEN ACCESS

Identification of defective Pt structure after neutron and ion irradiation

To cite this article: V A Ivchenko 2021 *J. Phys.: Conf. Ser.* **1799** 012012

Identification of defective Pt structure after neutron and ion irradiation

V A Ivchenko[1,2]

[1] Institute of Electrophysics, Ural Branch, Russian Academy of Sciences, 620016, Yekaterinburg, Russia
[2] Yeltsin Ural Federal University, 620002, Yekaterinburg, Russia

E-mail: ivchenko2008@mail.ru

Abstract. The adequacy of the effect of radiation exposure of different types on the same material (Pt) has been established. For this purpose, radiation defects of one type were studied using field ion microscopy (FIM). The structure of defects was studied on an atomically clean surface and in the near-surface volume of platinum after bombardment with neutrons and ion beams (E > 0.1 MeV and E = 30 keV, respectively). It is shown that the interaction of fast neutrons (E > 0, 1 MeV, $F = 6.7 \cdot 10^{21}$ m^{-2}, $F = 3.5 \cdot 10^{22}$ m^{-2}) with platinum leads to certain radiation damage in the volume. The same defects are observed when irradiated with Ar^+ ion beams (E = 30 keV, $F = 6.7 \cdot 10^{20}$ m^{-2}). The latter were found at a depth of about 1.5-2 nm from the irradiated surface. Thus, analog modeling of neutron and ion irradiation with a substance was performed.

1. Introduction

This work is devoted to the study of the spatial distribution of radiation damage (vacancies and their complexes) in HCC-metals (Pt) after various types of irradiation (neutron and ion beams).

Modeling of neutron irradiation by beams of positively charged ions allows solving the problem of analog modeling of various types of radiation.

The main goal of this work is to experimentally determine the adequacy of the radiation exposure of different radiations to the same material (Pt) when analyzing radiation damage of the same type.

For this purpose, radiation defects obtained in the material by bombardment with neutrons and ion beams (E > 0.1 MeV and E = 30 KeV, respectively) on an atomically clean surface and in the near-surface volume of platinum were studied. To solve the problem, we used the methods of field ion microscopy (FIM).

2. Experimental part

Platinum with a purity of 99.99% was used as the irradiation object. Using electrochemical polishing of wire fragments, needle emitters with a radius of curvature of the vertex of 30-50 nm were manufactured. Field emitters certified for ion implantation had an atomically smooth vertex surface prepared by field evaporation of surface atoms in situ.

Irradiation of needle samples certified in FIM was performed with Ar^+ beams with an energy of 30 KeV, a fluence of $F = 10^{18}$ ions/m^2, and a current density of $j = 150$ μA/cm^2 (T = 70°C). The bombardment was carried out in a direction parallel to the axis of the sample. Pre-certified and then implanted samples were re-placed in the FIM to study the material.

After neutron bombardment, samples were made from previously irradiated billets. The sample blanks were shaped like segments of platinum wire with a diameter of 0.2 mm and a length of 20 mm. The blanks were irradiated in the IBB-2M reactor at T = 310 K for an hour at neutron energy E >0.1 MeV and fluences F = 6.7 • 10^{21} m^{-2} and F = 3.5 • 10^{22} m-2.

Needle samples with a vertex curvature radius of 10-30 nm were obtained by electrochemical polishing and then placed in a FIM chamber. In the process of removing atomic layers from an atomically clean surface, ion images were recorded with a photo or video camera. This allowed us to analyze the structural state of Pt in volume.

The field ion microscope was equipped with a microchannel ion-electronic converter that allows increasing the brightness of the ion image of the surface by 10^4 times.

Liquid nitrogen (T = 78 K) was used as the refrigerant, and spectrally pure neon was used as the imaging gas.

3. Results and discussion

The study of the atomic structure of Pt after irradiation with neutrons up to 6.7 • 10^{21} m^{-2} (E > 0.1 MeV) revealed a large number of radiation damages to the crystal lattice [1]. Isolated point defects, vacancies, displaced embedded atoms, and clusters of vacancies were recorded.

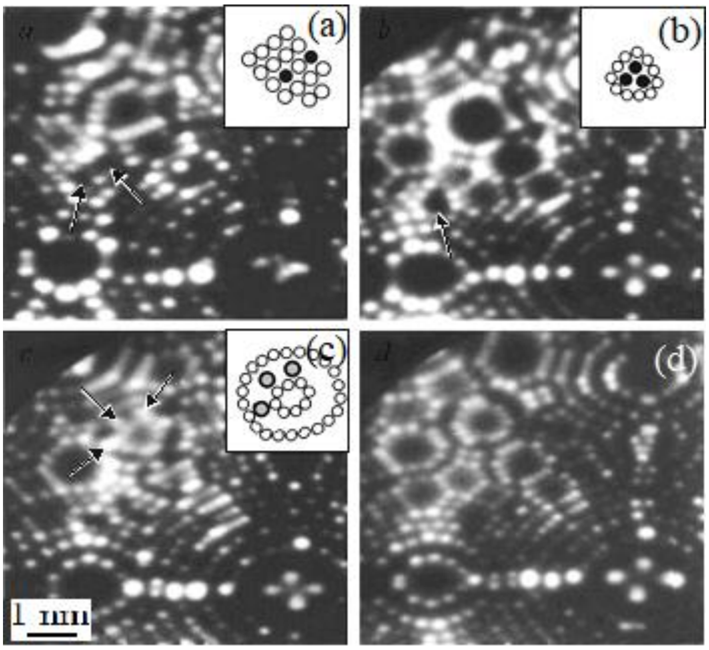

Figure 1. Neon images of platinum surface areas irradiated with neutrons with F = 6.7 • 10^{21} m^{-2}. Arrows show: **a**) individual vacancies, **b**) a tetrahedral cluster of vacancies, **c**) embedded atoms, and **d**) the same area of the surface without defects. The corresponding defect diagrams are shown in the upper-right corner: ○ - atom, ● - vacancy, and O - interstitial atom.

For controlled removal of surface atoms by an electric field, the ionic contrast of the typical spatial distribution of radiation damage in the Pt crystal lattice after irradiation with fast neutrons is shown in figure 1. The contrast of the image shows that the micro image of the surface of platinum exposed to fast neutrons is almost analogous to the image of the surface without irradiation. However, in some areas of the irradiated surface, violations of the ionic contrast of the ring pattern are observed. Radiation damage to the crystal structure is defined as violations of the ionic contrast of the ring pattern.

A particular type of defect that occurs in the material after irradiation is identified by a known type of contrast [2]. Consequently, the change in the ion contrast of the irradiated platinum compared to the certified Pt contrast is due to irradiation. This radiation damage occurs as a result of the interaction of neutrons with the atoms of the crystal lattice. The structure of the defect in the volume was analyzed during the controlled removal of platinum atoms by an electric field. Radiation damage usually consisted of individual point defects (vacancies and interstitial atom atoms) or small clusters of vacancies of a size comparable to interatomic distances.

When the neutron fluence was increased to 3.5 • 10^{22} m^{-2}, depleted zones with a higher local concentration of vacancies and ring zones of embedded atoms were found, figure 2. This result confirms the hypothesis [3]. According to [3], the development of a cascade in a metal occurs in such a way that a large number of atoms are removed from the central part of the cascade (the most disturbed region) by means of substitution chains. The average concentrations of vacancies and embedded atoms in the depleted regions were, according to our estimates, 9 and 1.5%, respectively.

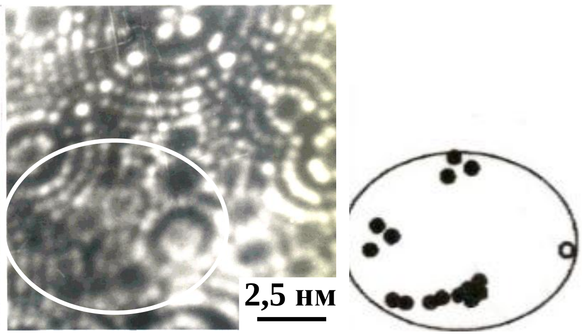

Figure 2. The section of the ion contrast of the platinum surface, after neutron bombardment, F = 3.5 • 10^{22} m^{-2} (depleted zone: ● - vacancy; ○ - embedded atom) and the corresponding scheme of the spatial distribution of the defect.

The study of a large number of micro images of the irradiated platinum surface made it possible to measure the longitudinal and transverse dimensions of individual depletion zones. As a result, the average diameter of the radiation cluster was determined, which was 3.2 nm.

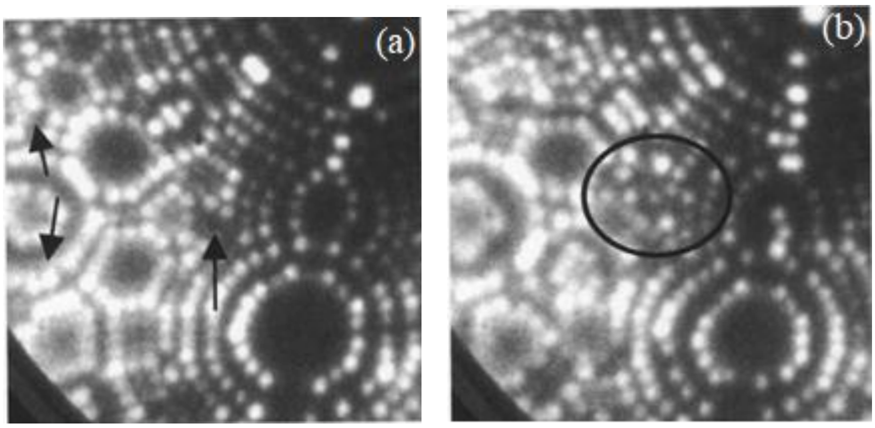

Figure 3. Ionic contrast of the Pt surface area after irradiation with Ar^+ beams E=30 Kev, F = 10^{18} ion/m^2 and j = 150 μA/cm^2 (T = 70°C): **a** - at a depth of 2 nm from the irradiated surface (arrows indicate isolated vacancies and embedded atoms); **b** - at a depth of 1.5 nm from the surface (the depleted zone is shown).

As a result of neutron irradiation of Pt to 6.7 • 10^{21} m^{-2} (E > 0.1 MeV), the structural state of the pure metal changed slightly, as evidenced by micrographs recording the atomically pure surface of the irradiated platinum, figure 1. In micrographs, defective surface areas were observed, where the result of interaction with neutrons was detected in the form of displacements of atoms from the lattice sites. Radiation damage usually consisted of individual vacancies, small clusters of vacancies, individual atoms, and zones of atoms displaced from equilibrium positions. Thus, it can be argued that the influence of the above-mentioned neutron fluence creates separate, non-overlapping cascades of atomic displacements in platinum.

As can be seen, the ion contrast of radiation damage after ion irradiation (figure 3) differs from the contrast of radiation damage after neutron interaction with the material (figure 2). Further study of the near-surface volume of Pt after ion irradiation by successive field evaporation of atomic layers at a depth of 1.5 nm from the surface revealed radiation damage identical to the damage in figure 2. The ion contrast from such radiation damage is shown in figure 3b.

The interaction of fast neutrons (E > 0.1 MeV) $F = 6.7 \bullet 10^{21}\ m^{-2}$ leads to the formation of such radiation damages in the volume of platinum, which after ion irradiation with charged beams of Ar^+ ions with E = 30 Kev, $F = 10^{18}$ ions/m^2 are observed in Pt at a depth of about 2 nm from the irradiated surface.

4. Conclusions

It is established that all radiation damages in the volume of the material after neutron irradiation are lattice defects of a certain type, which depend only on the fluence and neutron energy. On the contrary, when charged ion beams interact with a substance, the type of radiation damage is determined, in addition to the irradiation parameters, by the distance from the irradiated surface. At different depths of the material, the process of transition from one type of radiation damage to another is observed. Therefore, the analog of the fast neutron effect at a certain fluence with the effect of ion irradiation can be fully modeled only at a certain depth of the near-surface volume of the substance irradiated by Ar^+ beams.

As a result, it was found that the interaction of fast neutrons with the material corresponds to the action of charged beams of Ar^+ ions at a certain depth from the irradiated surface. It follows that it is possible to model the effect of neutron irradiation by beams of charged ions based on the occurrence of a certain structure of radiation damage in the material.

Acknowledgments

The work was performed within the framework of the state task theme.

References

[1] Ivchenko V A, Medvedeva E V and Ovchinnikov V V 2009 *Poverkhnost'. Rentgen., Sinkhrotr. Neitron. Issled.* **8** 26

[2] Boowkett K M and Smith D A 1970 *Field Ion Microscopy Defects in Crystalline Solids* (Amsterdam, London: North Holland Publishing Company)

[3] Seeger A K 1958 *Proceeding of The Second Intern. Conf. on Peaceful Uses of Atomic Energy* (Geneva: United Nations)

[4] Ivchenko V A and Medvedeva E V 2009 *Izv. Vysch. Uchebn. Zaved. Fiz.* **8** 410